Ball Aerospace & Technologies Corp.

CINDIS
Cold Interferometric Nulling Demonstration In Space

Charley Noecker   Roger Linfield   Dan Miller

David Osterman   Steve Kilston   Mike Lieber

Bill Babb   Andrew Cavender   Jack Jacobs

Honeywell

TPF Expo 2003 – Pasadena

Motivation

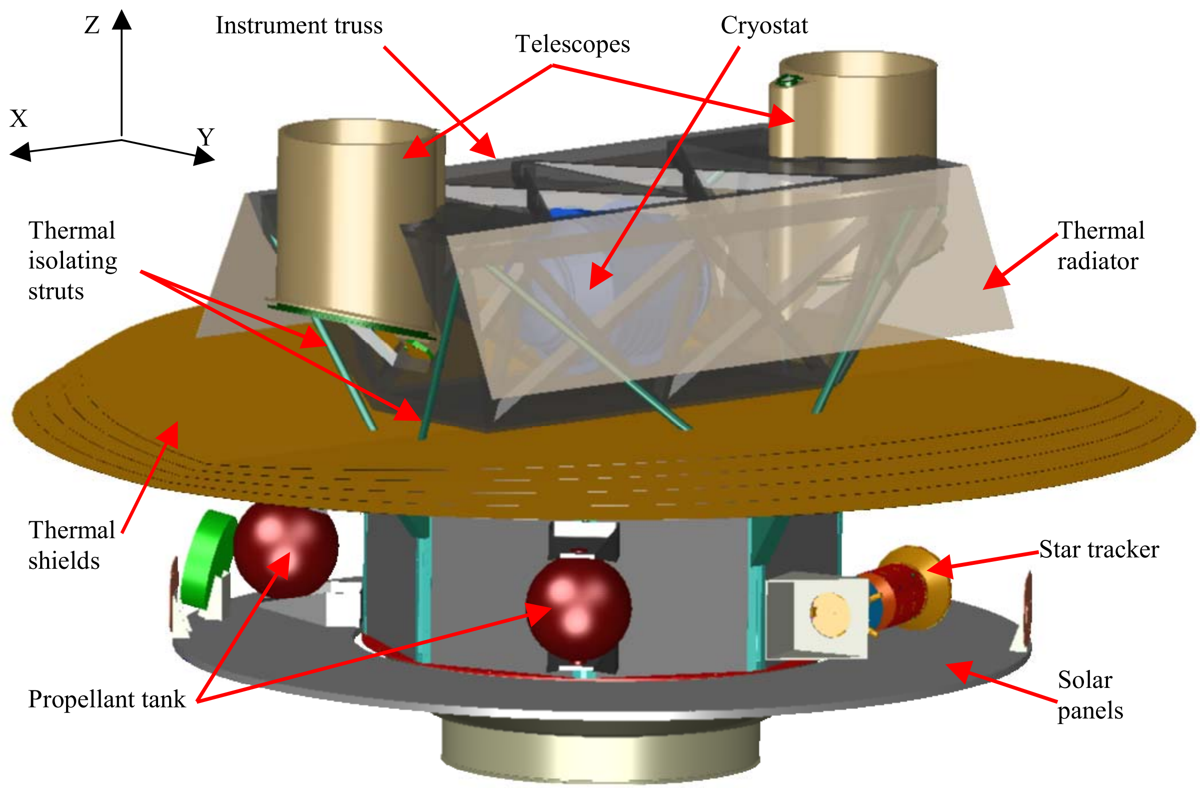
- Extra-Solar Planets Advanced Concepts NRA
  - Category 2 – Space mission for TPF technology demonstration
  - Cost guideline $300M
- Phase 1 study – <u>technology demo only</u>
  - Three objectives, in this order of priority:
    - Adhere to $300M cap
    - Maximize technology demonstration value to TPF
    - Enable useful scientific investigations
  - This "unusual" ordering led to a design which is smaller and simpler than a science-oriented interferometer would be
- Phase 2 study – <u>add compelling science</u>
  - Upgrades which would cost-effectively enable science

➔Suggest scope for a possible <u>technology</u> and <u>science</u> precursor mission

The "Phase 1" CINDIS design

- Technology demonstration mission for TPF interferometers
- First nulling interferometry in space, on a fixed structure

Wavelength range	6-12μm
Optics temperature	~50K
Telescopes	2 (4 goal)
Telescope diameter	40 cm
Baseline	2 m
Cryogen	Solid H_2
Deployments	Shades
Orbit	L2/SIRTF
Total mass	472 kg
Total power	307 W

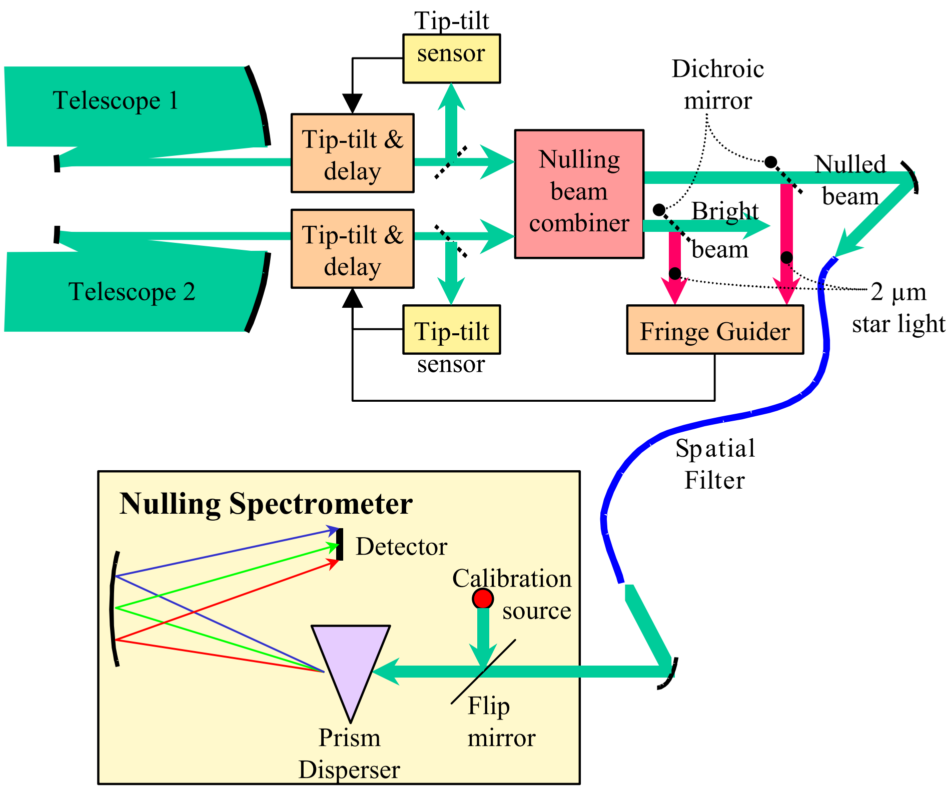


Features of the "Phase 1" system

- Baseline ~2 meters
  - No science requirements for a minimum baseline
  - Non-deploying optical structure fits horizontally in launch shroud (simplest approach)
  - Optional soft structure (1st mode~ 5Hz); strongback for launch & early observations
    - Demonstrates vibration isolation for longer TPF structures; further model validation
- Warm-side active isolation system
  - Suppresses vibrations to a level sufficient for a deep null
  - Low-risk way to provide a quiet platform for the nulling demonstrations
- Stored cryogen
  - Cools Si:As detectors for low noise
  - Cheapest and most reliable cooling system for a short (6-9 month) mission
- Drift-away orbit
  - Good thermal stability
  - Easy passive cooling

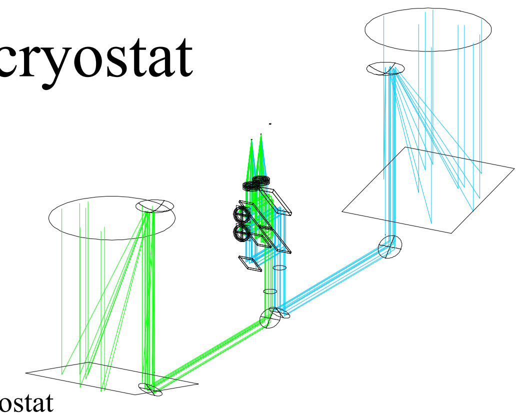
Optical schematic (Phase 1)

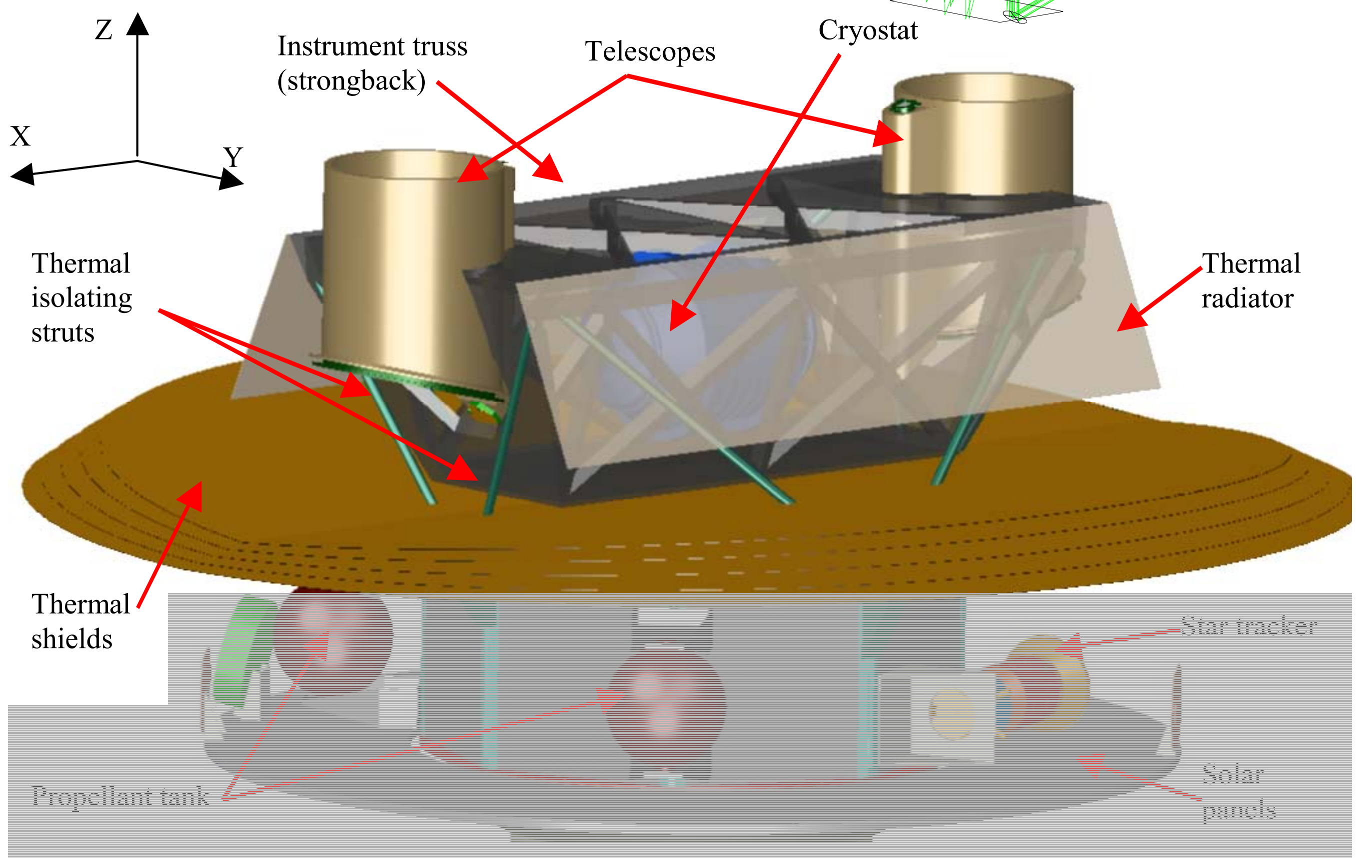
- Standard 2-aperture design (Bracewell)
- Controls (sensors, actuators) for tip-tilt and piston
- Nulling combiner sums optical fields with a wavelength-independent 180° phase offset
  - Several designs under development around the world
- Spatial filters after nulling combiner
- Low-resolution spectrometer ($\lambda/\Delta\lambda \sim 3$–20)



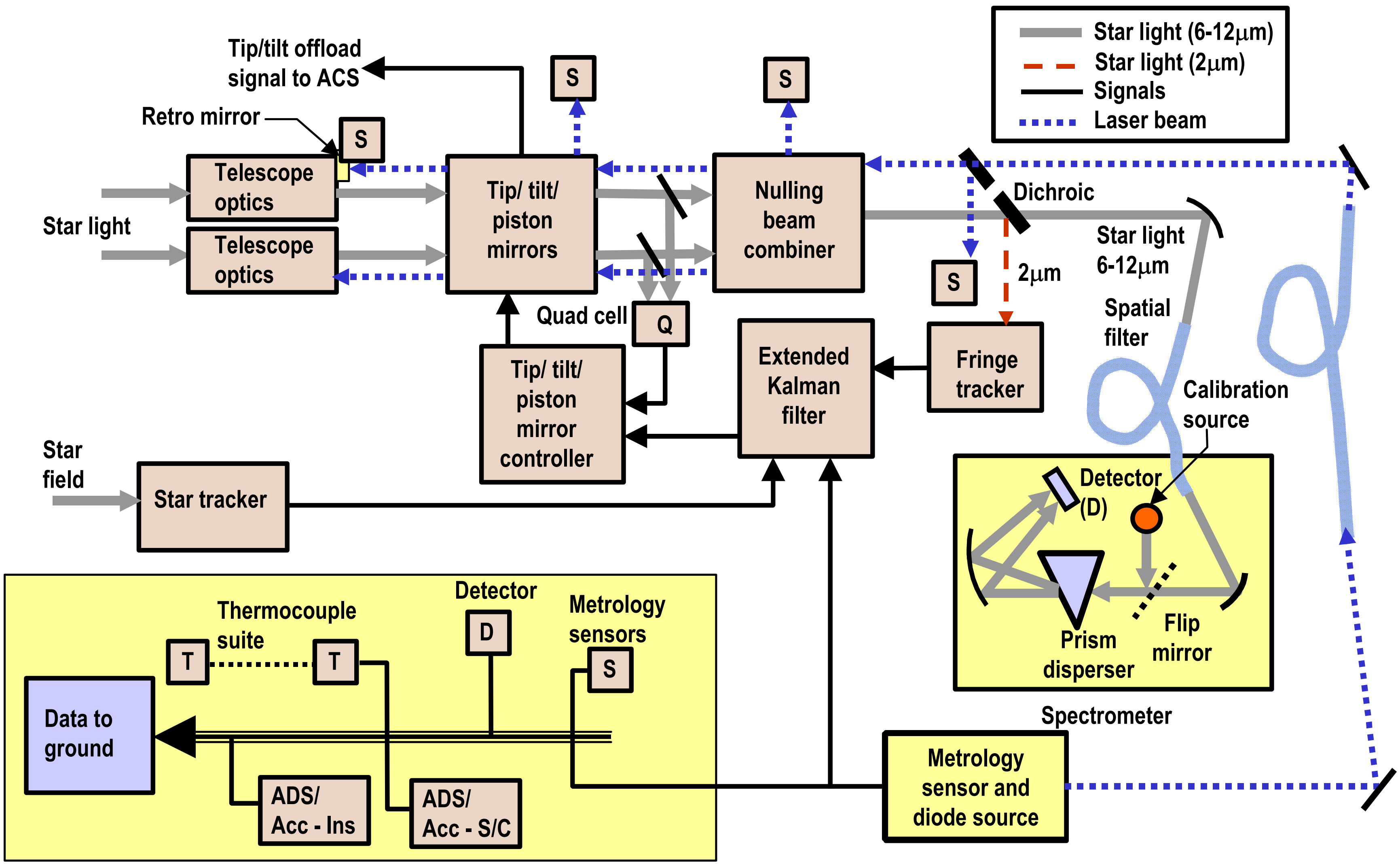
Instrument Features (Phase 1 system)

- Nulling combiner is entirely contained in Solid-H_2 cryostat
  - 8 kg H_2 provided
- Wavelength range 6-12 μm
- Strongback for launch
- Deployable thermal shield
  - 50K passive cooling
- Gamma-alumina struts
- 2 m^2 radiators



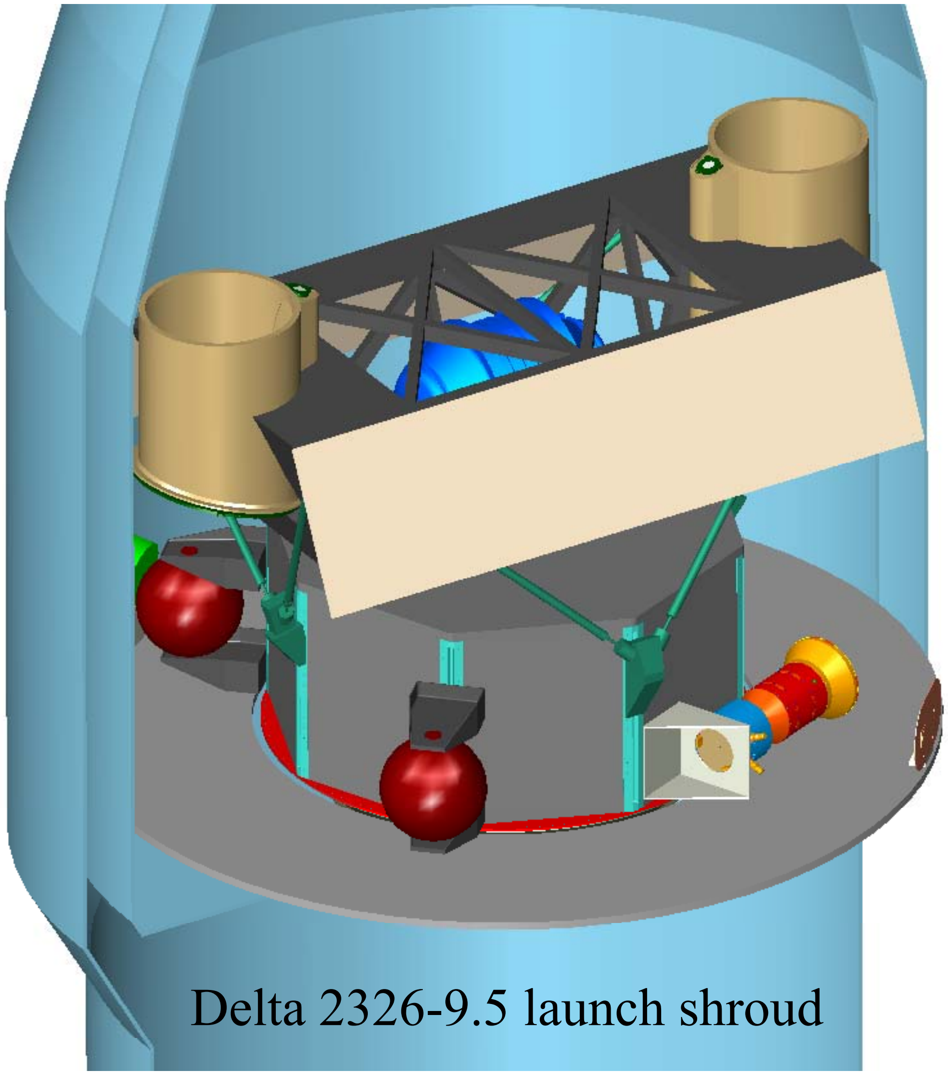


Instrument Controls Diagram (Phase 1)



Spacecraft features (Phase 1 system)

- Based on the Ball RS-300 small S/C functional architecture
- Single-string
  - Minimizes mass & cost
  - High probability of mission success for 6-month mission
  - Heritage for multi-year single-string buses
- Ball's ASPEN integrated hardware & software avionics suite
- Earth-trailing drift-away orbit
- Delta 2326-9.5 launch vehicle
- Cold gas reaction control system



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Parameter	**Allocation**	**Predicted Performance**
S/C Bus Mass	245 kg	198 kg
S/C Bus Power	208 W	177 W
Instrument Power Allocation	100 W	65 W
Attitude Control	3-axis stabilized	3-axis stabilized
Pointing Accuracy (X & Y, 3-σ per axis)	3 arcsec	1.5 arcsec
Pointing Accuracy (Z axis, 3-σ per axis)	30 arcsec	15 arcsec
Incident Solar and Bus Parasitic Heat Load Transmitted to Instrument	< 0.5 W	< 0.4 W
Sunshield Off-Pointing (maximum angle from sun line)	30°	30°
Instrument Data Storage	<154 MB / week	154 MB / week
Downlink Data Rate	100 kbps	> 380 kbps
Uplink Data Rate	500 bps	2 kbps

Parameter	**Value**
Launch Date	June 1, 2007
Launch Vehicle	Delta 2326
Mission Duration	6 months
Orbit Type	Earth-Trailing, Heliocentric
Max Earth Range	0.07 AU
Max Sun Range	1.04 AU
SPE Angle at L+30 D	56 degrees

Pointing and delay jitter performance with Honeywell VISS

Pointing and delay jitter meet requirements with

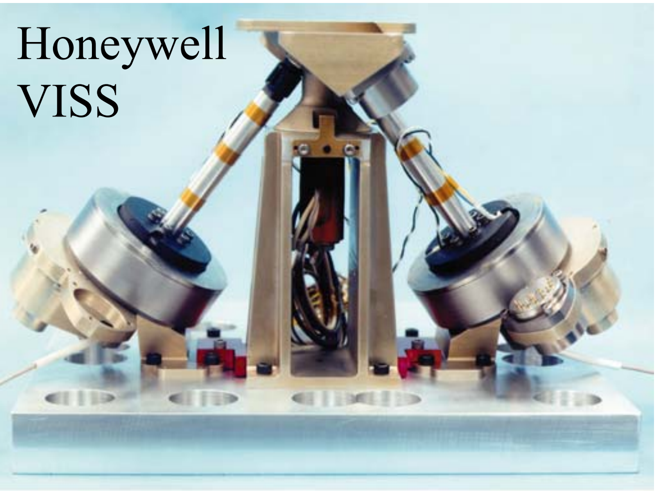
5 Hz truss (soft like 40m TPF)

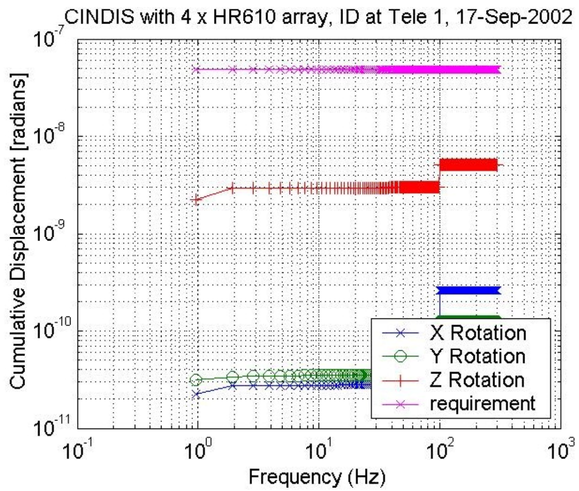
+

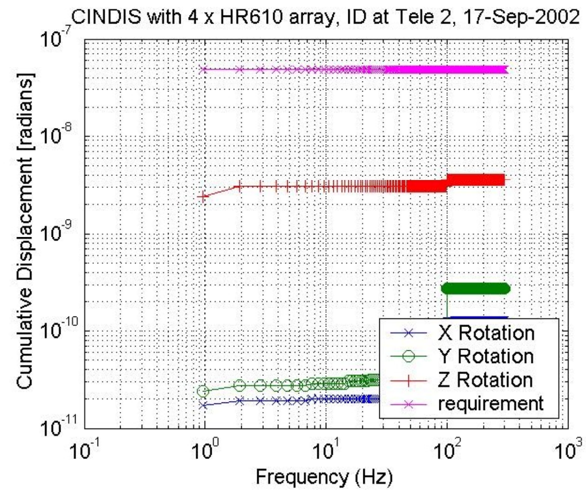
Honeywell's Vibration Isolation & Suppression System (VISS) at bus-instrument interface (warm)

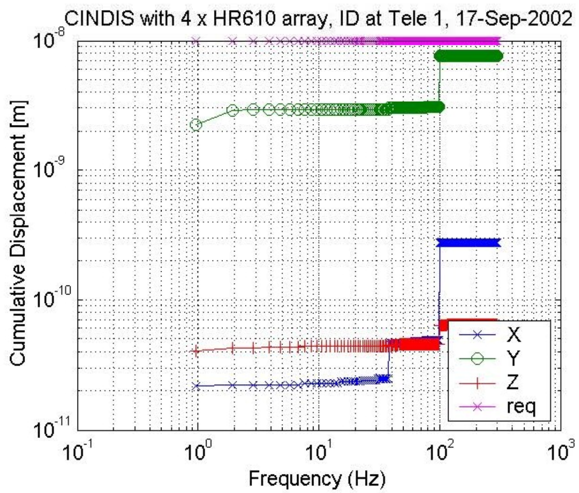
+

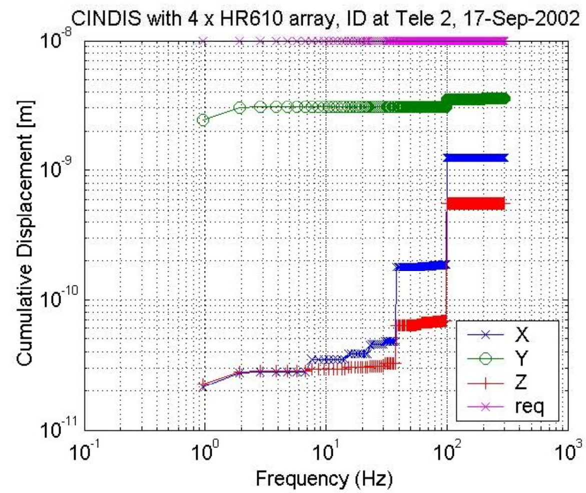
Passive dampers (0.1%) on truss



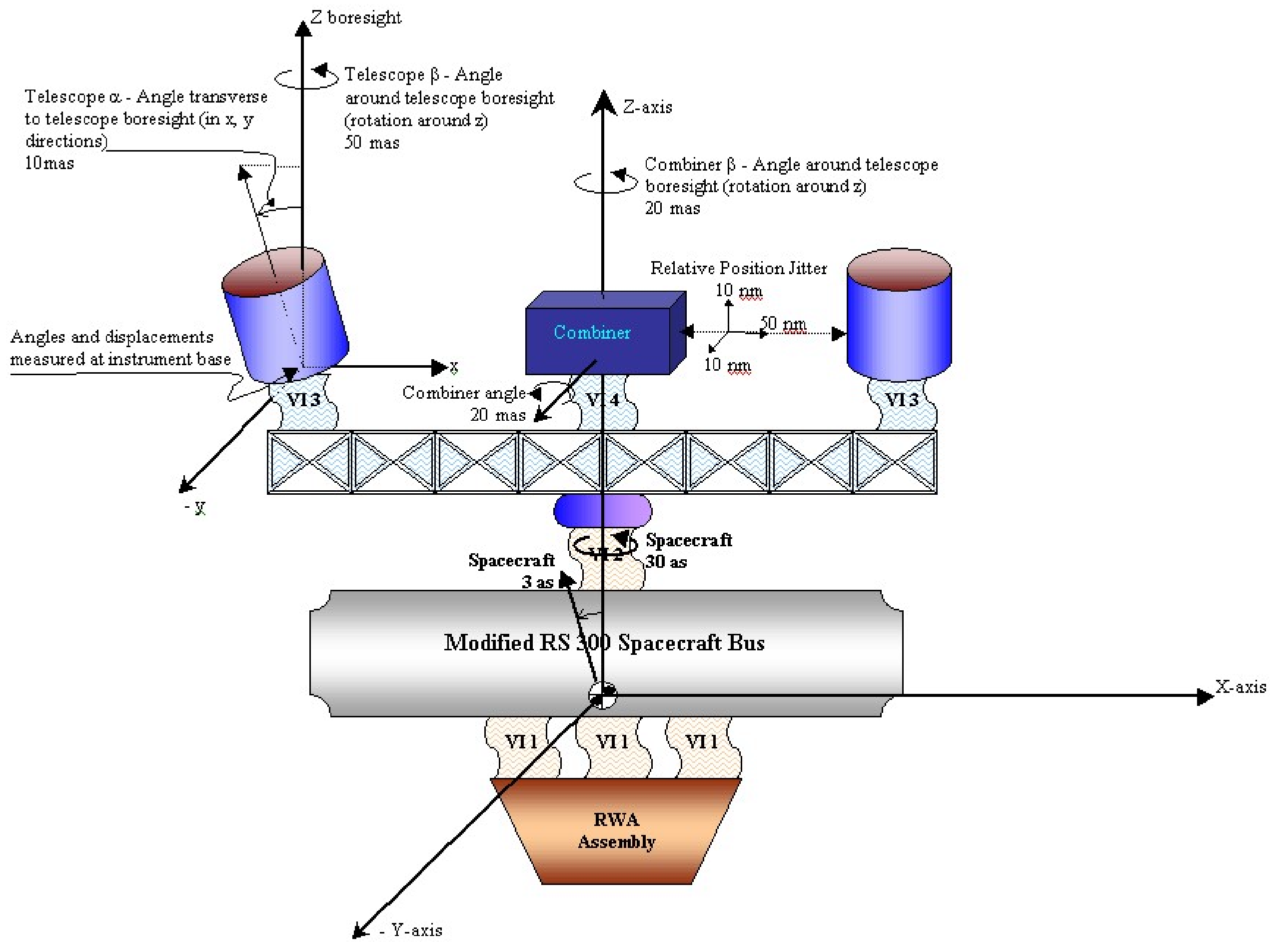








Controls Allocations for Structural Jitter in Pointing and Optical Delay



Assumes instrument control systems can suppress remaining jitter

Architecture changes for Phase 2 CINDIS

- Dual Bracewell (4 telescopes)
  - Control of systematic error sensitivity → sufficient for finding planets
  - Suppress signals from exo-zodi → reduce/eliminate confusion source
  - Fully demonstrates the same technologies needed for TPF
- Longer baseline (15m+)
  - Angular resolution adequate to find known extrasolar giant planets
  - Structural vibration control scalable to full size TPF
- Expandable truss
  - Efficient packaging, stable structure
- Apertures 0.4 m diameter
  - Adequate for controls, planet detection
  - Preliminary value, TBR

Mission requirements (Phase 2)

- Principal objectives
  - Demonstrate direct detection of planets at near-TPF-level sensitivity
  - Deliver a wealth of performance data to inform TPF system engineering

	CINDIS Phase 1 req't/goal	CINDIS Phase 2 req't/goal	TPF	Remarks
Null depth	10^{-5} / 10^{-6}	10^{-5} / 10^{-6}	10^{-6}	Keep small to aid stability
Null depth stability (planet-mimicking systematics)	2.5×10^{-7} / 2.5×10^{-8}	2.5×10^{-7} / 2.5×10^{-8}	2.5×10^{-8}	Keep systematics <20% of planet (1–10 × earth)
Angular resolution	No req't	150 mas / 80 mas	40	Added req't to observe some planets
Optical passband	>6 μm	7-12 μm	7-17 μm	"Instrument similar to TPF" vs. "do planet science"
Stability time-scale	0.08 hour	5-10 hr	5-10 hr	Demonstrating instrument vs. seeing planets
Number of stars	6-10	6 / 30	30-150	Now have specific stars
Sky coverage (maximum angle from anti-sun)	30°	30°	>45°	Need access to known target stars
Rotation around LOS	45°	180°	180°	Demo vs. planet search

Planet detection depends on both null depth and long-term stability of the system

- Photon counting noise is not the only limitation to planet sensitivity
- Also must consider systematic variations which mimic planet signals

- Without chopping, a major concern is systematics at ~DC (few milliHertz)
  - Example: 2 aperture Bracewell
  - Stellar leakage + instrument thermal emission + astronomical backgrounds must be stable to < ~1/5 planet
  - 2.5×10^{-8} of star flux at few mHz

- Phase-chopping architectures put planet signature at ~0.1 Hz
  - ➔Insensitive to mHz signal drifts
  - BUT other systematic problems appear on the same time scales
- Technology objective: demonstrate controls adequate to counteract dual Bracewell systematic errors

Tighter budget for null depth makes it easier to meet stability requirements

Single Bracewell example	Requirement (10^{-5} null)	Stability for "Earth" detection	Goal (10^{-6} null)	Stability for "Earth" detection
Intensity match	2.8×10^{-3}	8×10^{-6}	9×10^{-4}	2.6×10^{-5}
Delay jitter	4.5 nm	0.013 nm	1.4 nm	0.04 nm
Polarization rotation	10 arcmin	0.03 arcmin	3 arcmin	0.09 arcmin
Tip-tilt (sky angles) (Airy radii)	9 mas 1.5×10^{-3}	0.026 mas 4.3×10^{-6}	2.8 mas 4.7×10^{-4}	0.083 mas 1.4×10^{-5}
Wavefront error	4.5 nm rms	0.013 nm rms	1.4 nm rms	0.04 nm rms

- Equal budget allocations for 5 terms
- Tighter null depth ➔ looser stability req't ~ 3% of tolerance
- Looser null depth ➔ tighter stability req't ~ 0.3% of tolerance
- Tighter fractional stability of these quantities is a higher risk

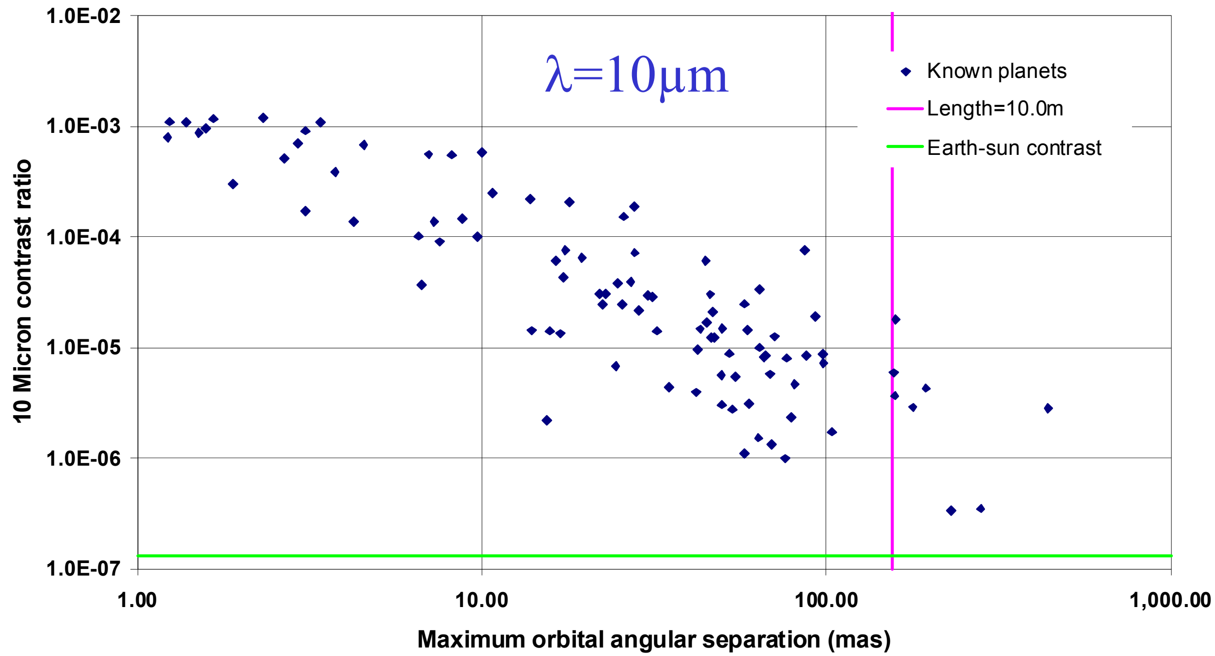
Stellar companions as science targets

- Known companions: Older EGPs, brown dwarfs
- Expected/unknown: Hot young EGPs, EGPs not found by RV
- Prefer older planetary systems
  - Lower EZ dust levels → easier planet detection
  - Best TPF candidate stars will be older
- Prefer contrast $\sim 10^{-5}$ or fainter
  - Take on technical challenge comparable to TPF, not 100-1000x easier

Known extra-solar giant planets

- "Desert" – gap in distribution of planets vs. angle at 100-150 mas
- Six planets have
  - Contrast $>3\times10^{-6}$
  - Max angle > 150 mas
  - Requires >76° sky coverage
- Six planets have
  - Contrast $>1\times10^{-6}$
  - Max angle > 96 mas
  - Ecliptic latitude < 30°

Planet/star contrast vs. angular separation

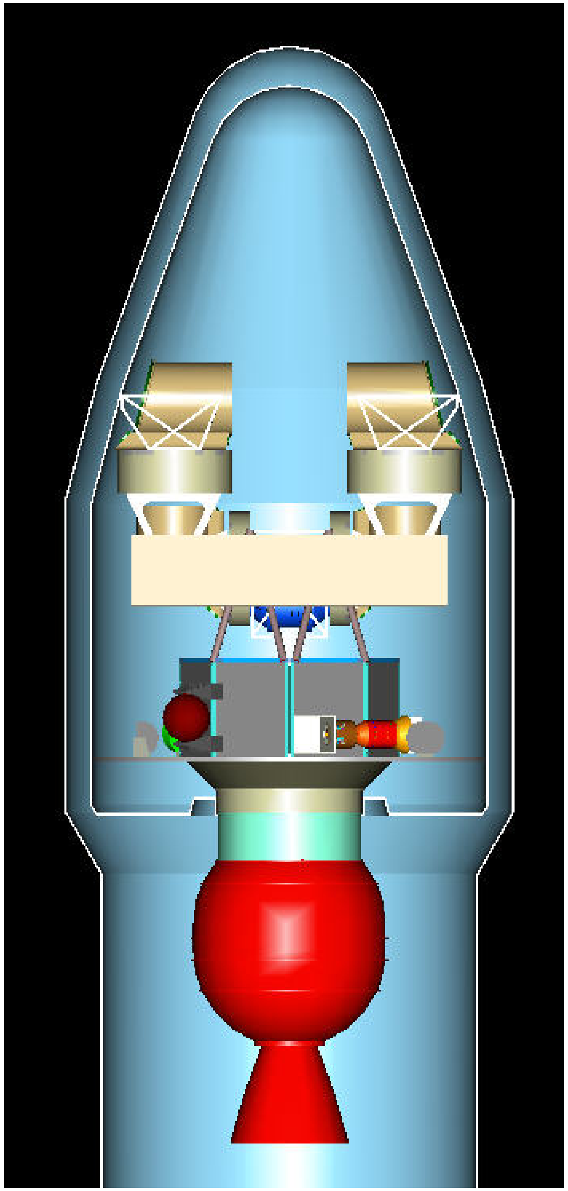


Brightness and contrast for planet are calculated assuming 3Gyr age

- Second option preferred
  - Only need a sunshade for 30° from anti-sun
  - Beyond the desert ➔ increasing length gives more planets

Phase 2 CINDIS in the Delta 2326-9.5 launch shroud

- Expandable truss, 15m+
  - "Able mast" or equivalent
  - Studies indicate this construction can be made sufficiently stable
- Telescopes mount on top
  - Apertures 0.4m diam, TBR
- Multi-layer sunshade deploys with boom
  - Allows >30° from anti-sun



Dual Bracewell performance allocations

- Performance budget tables
  - Null depth
  - Systematic errors

RMS aberr phases (rad)					
Nuller A-B dif	(A+B)/2 avg	variation			Stability
2.05E-03	2.05E-03	4.10E-05	piston	3.27E-09 m jitter	6.53E-11
2.70E-03	2.70E-03	5.40E-05	focus	4.30E-09 m rms	8.59E-11
1.35E-02	1.35E-02	2.70E-04	sph_ab	2.15E-08 m rms	4.30E-10
4.00E-02	4.00E-02	8.00E-04	tip/tilt	8.91E-07 rad	1.78E-08
2.00E-02	2.00E-02	8.00E-04	coma	31.83 nm	1.27 nm
1.00E-02	1.00E-02	1.00E-03	astig	15.92 nm	1.59 nm
2.00E-03	2.00E-03	1.00E-03	trefoil etc	3.18 nm	1.59 nm
0.20%		2.00E-05	ampl imbal (λ indep)		
		8.17E-04	cophasing		1.30 nm
		1.67E-05	Effective baseline		2.50E-04 m
		2.00E-05	zeta		1.00E-04 m

	multi-plier		Leak	Leak variation
Total star leakage (tot)			2.09E-05	1.00E-07
Stellar disk leak			1.26E-05	4.51E-10
Instrument null depth			8.33E-06	1.00E-07
Leak due to phase			5.72E-06	8.78E-08
Phase errors	× 2	2.39E-03		↑
OPD		2.05E-03		8.42E-08
Focus		-9.50E-04		1.79E-08
Other WFE		7.78E-04		1.72E-08
Leak due to amplitude			2.33E-06	4.45E-08
Amplitude errors	× 2	-1.43E-03		↑
Tip-tilt	× 2	-6.37E-04		3.06E-08
Coma	× 2	4.40E-06		1.10E-08
astig	× 2	-3.54E-05		1.01E-08
trefoil etc.	× 2	-1.32E-06		1.88E-09
focus+sphab	× 1	-8.68E-05		
Ampl imbalance	× 2		1.48E-07	-2.85E-08
Polarization	× 2		2.80E-07	5.00E-09
biref			7.00E-08	
diatten			7.00E-08	
Cophasing of nullers A & B				1.03E-08
Amplitude-phase cross-terms				1.50E-08
Optics thermal emission				8.65E-08
Solar stray light				8.65E-08
Exo-zodiacal light				8.65E-08
Local zodiacal light				8.65E-08

Data harvest

In addition to science measurements, CINDIS will produce a rich characterization of the instrument performance

- Extensive suite of diagnostic sensors is integrated into the design
- Verify performance of components & subsystem controls
  - Active delay and pointing control
  - Passive amplitude and polarization matching
- Verify system null depth and null stability budgets
- Study thermal control & stray light
- Compare instrument performance to budgets and model predictions
  - Establishes a strong foundation for TPF system engineering

CINDIS Phase 1 Optical System Model

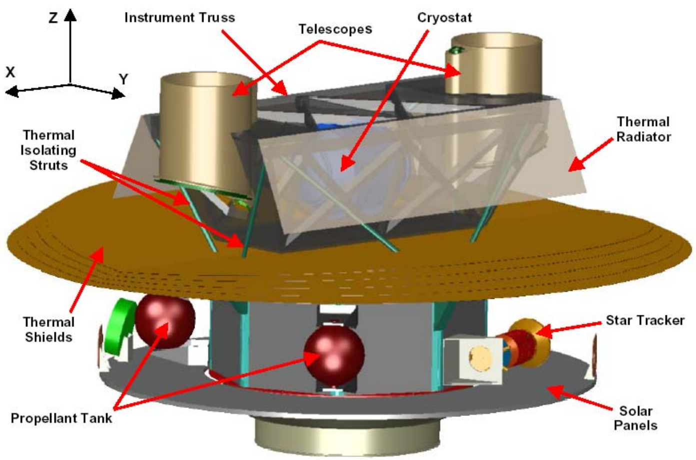
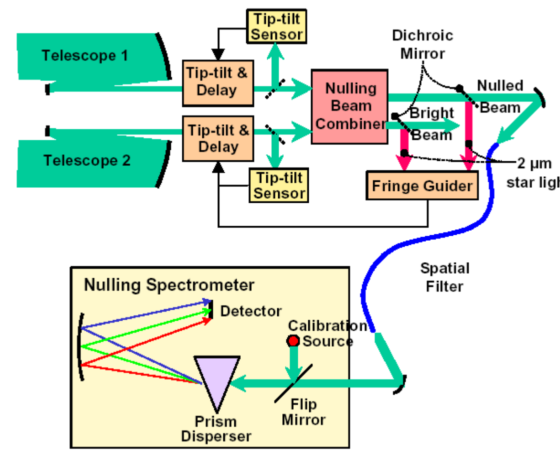
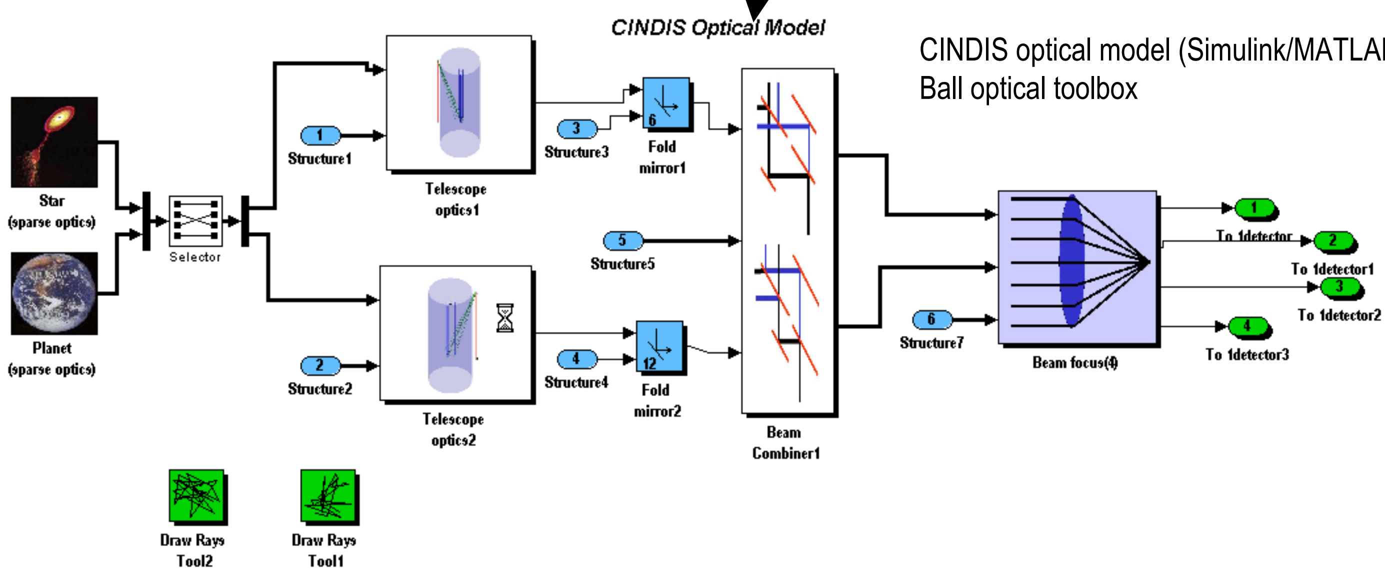


Figure 1 CINDIS on-orbit configuration.

CINDIS optical layout

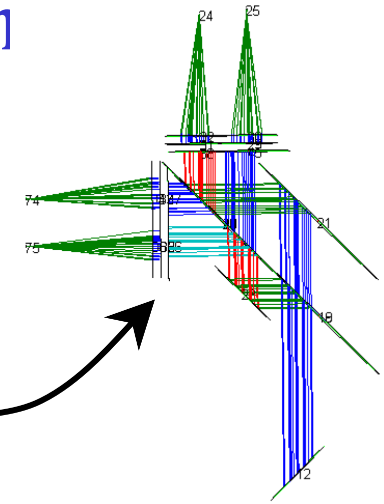


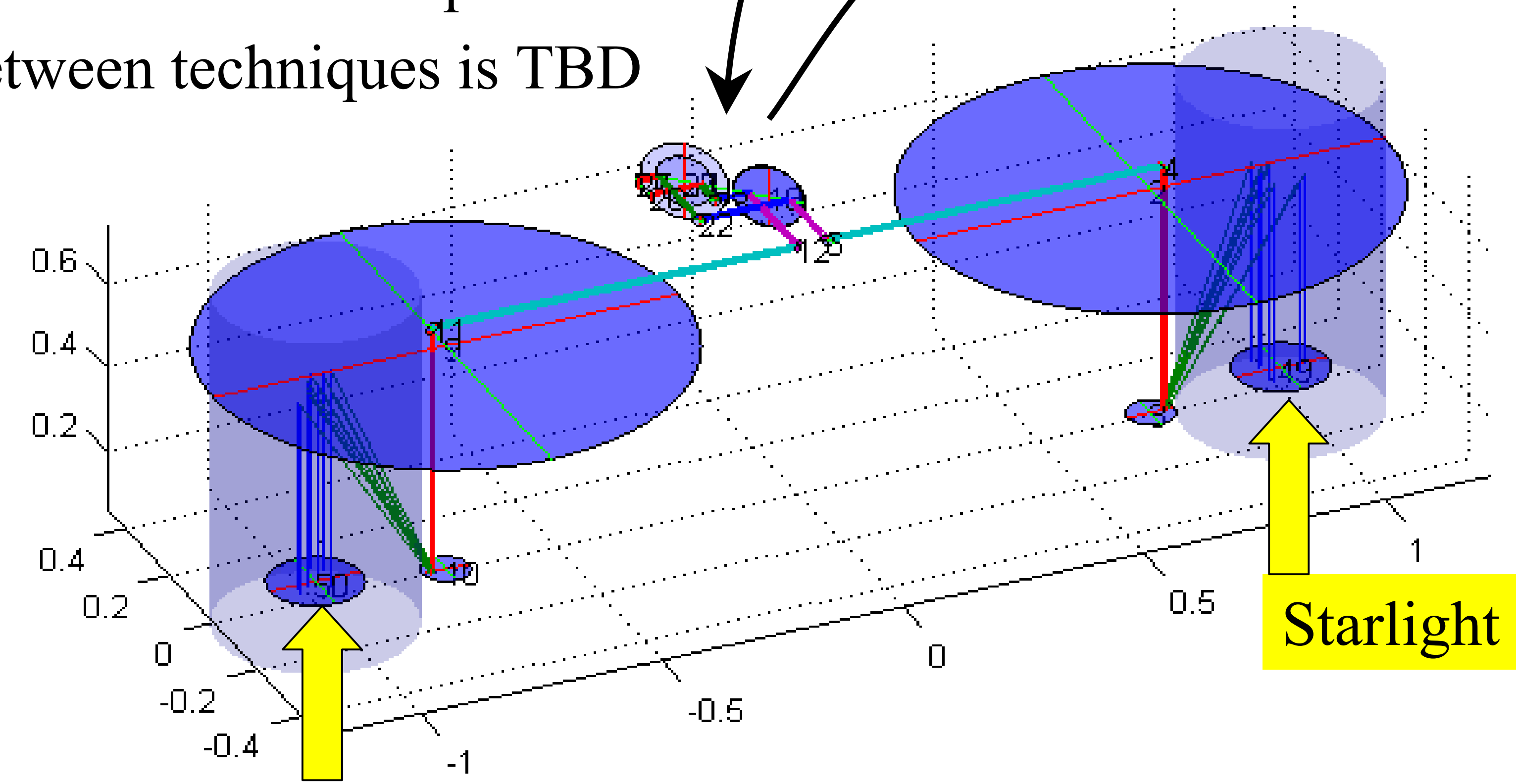


CINDIS optical model (Simulink/MATLAB) – Ball optical toolbox

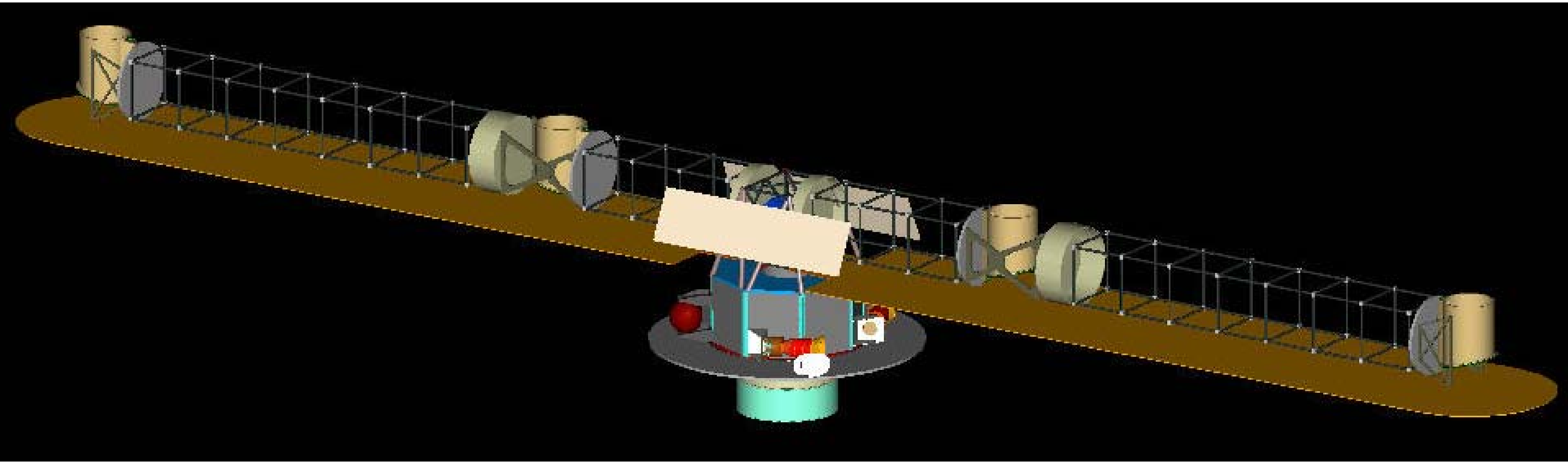
CINDIS Phase 1 optical path

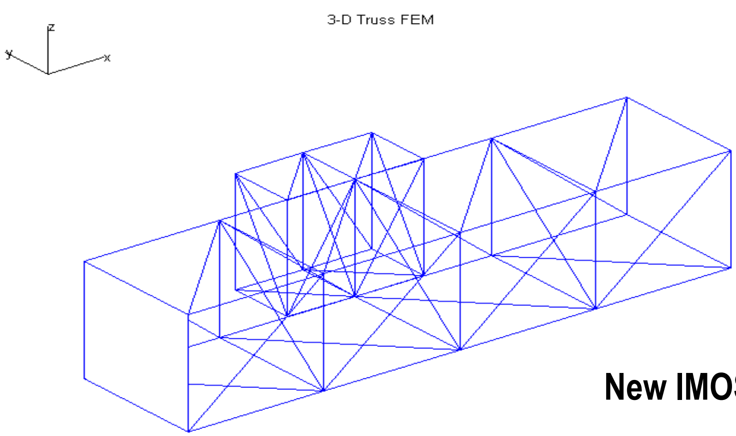
- Folding beams out to the side, as shown, gives an achromatic π phase between telescope beams
- Dielectric plate technique also a candidate for achromatic π phase
- Choice between techniques is TBD





CINDIS Phase 2 deployed

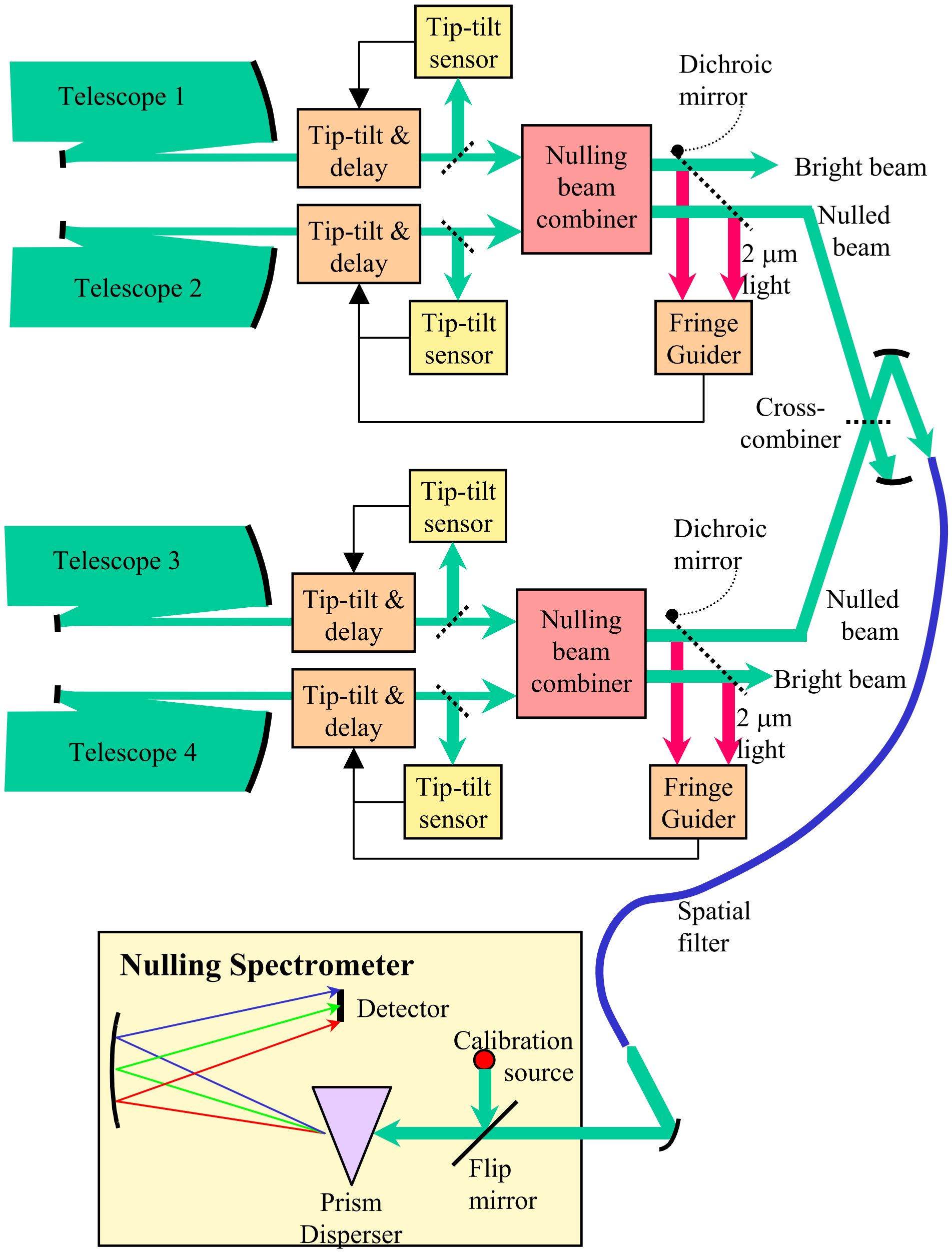




New IMOS based truss structure

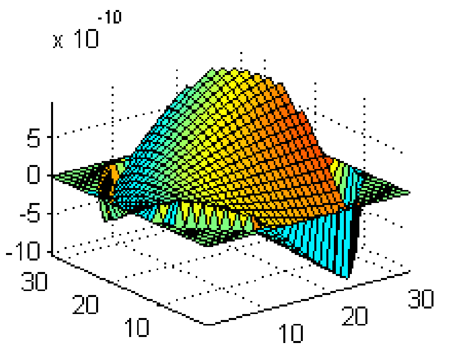
CINDIS Phase 2 optical schematic

Dual Bracewell

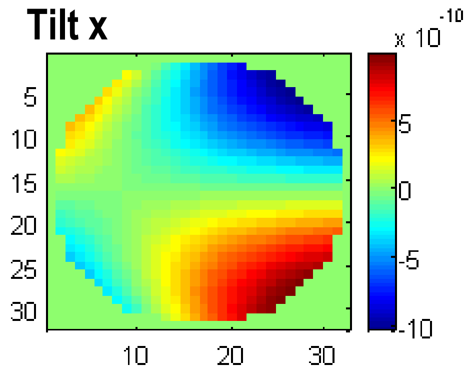


Residual from Tilt of Telescope Axis with FSM Correction

- Residual due to effect of telescope working off-axis
  - 100 nrad tilt = 0.0033 Airy, telescope diam 0.4m

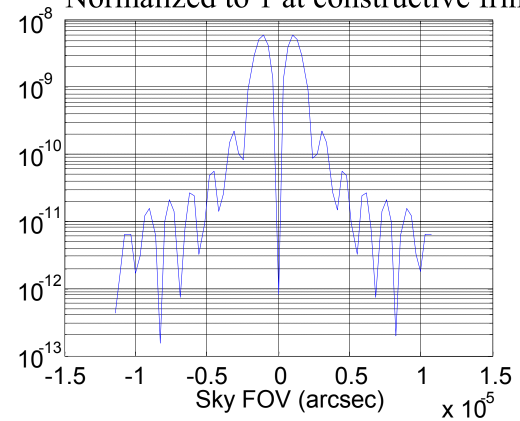


Tilt x

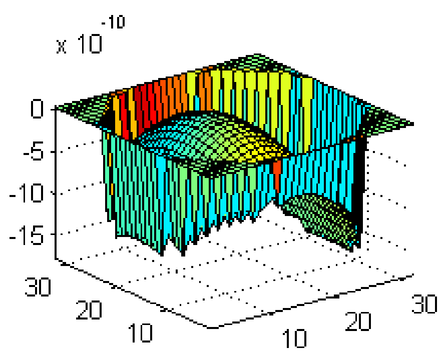


Intensity at spatial filter entrance

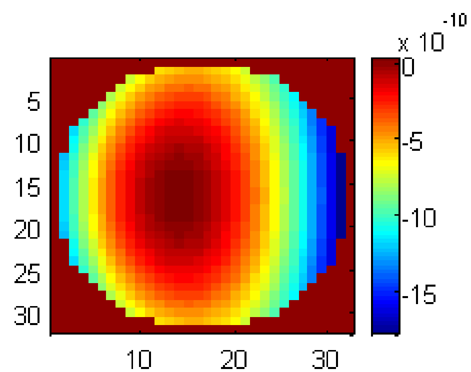
Normalized to 1 at constructive fringe

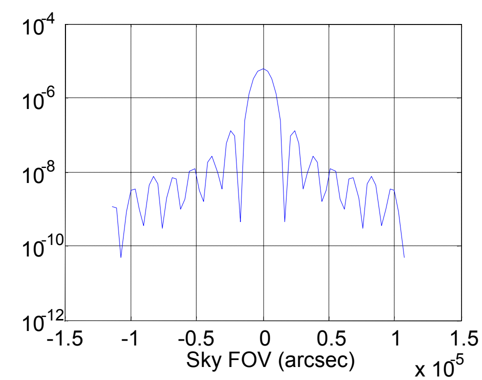


For 60× larger tilt than this (6μrad), stellar leak after spatial filter ~5×10^{-9}



Tilt y

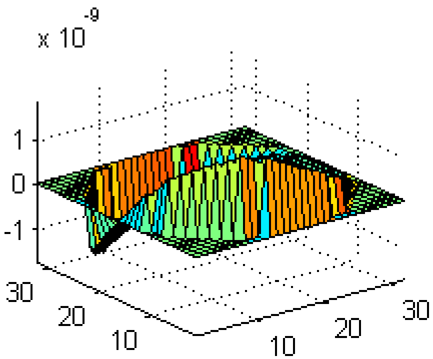


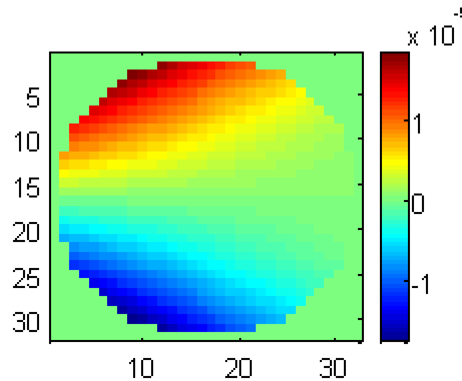


For just this tilt (0.1 μrad), stellar leak after spatial filter ~2.5×10^{-9}

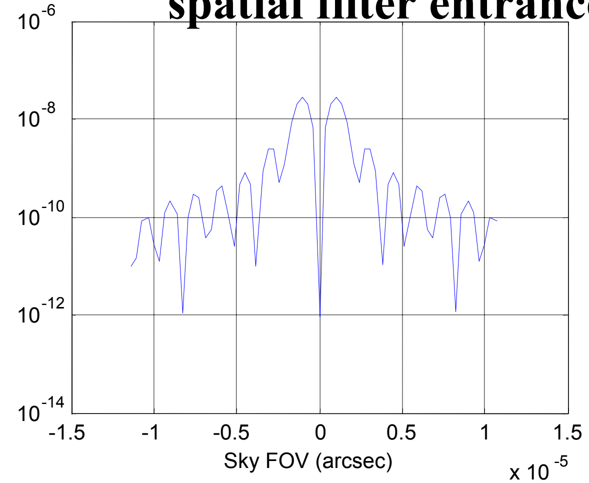
Residual from distortion within telescope body

- Tilt primary with respect to secondary





Intensity at spatial filter entrance

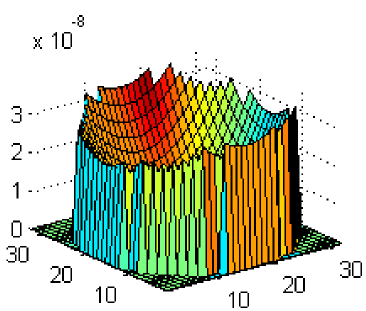


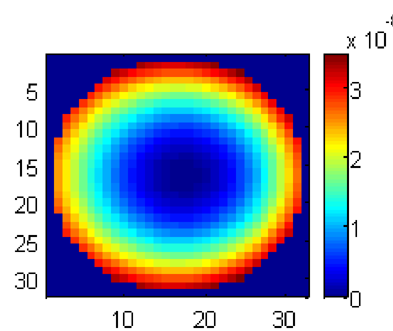
➔ Spatial filter

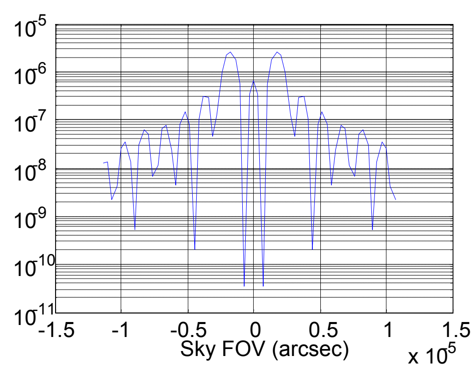
For 3µrad tilt, stellar leak after spatial filter is ~2×10^{-9}

Residual from telescope despacing

- Move primary to secondary (10nm).

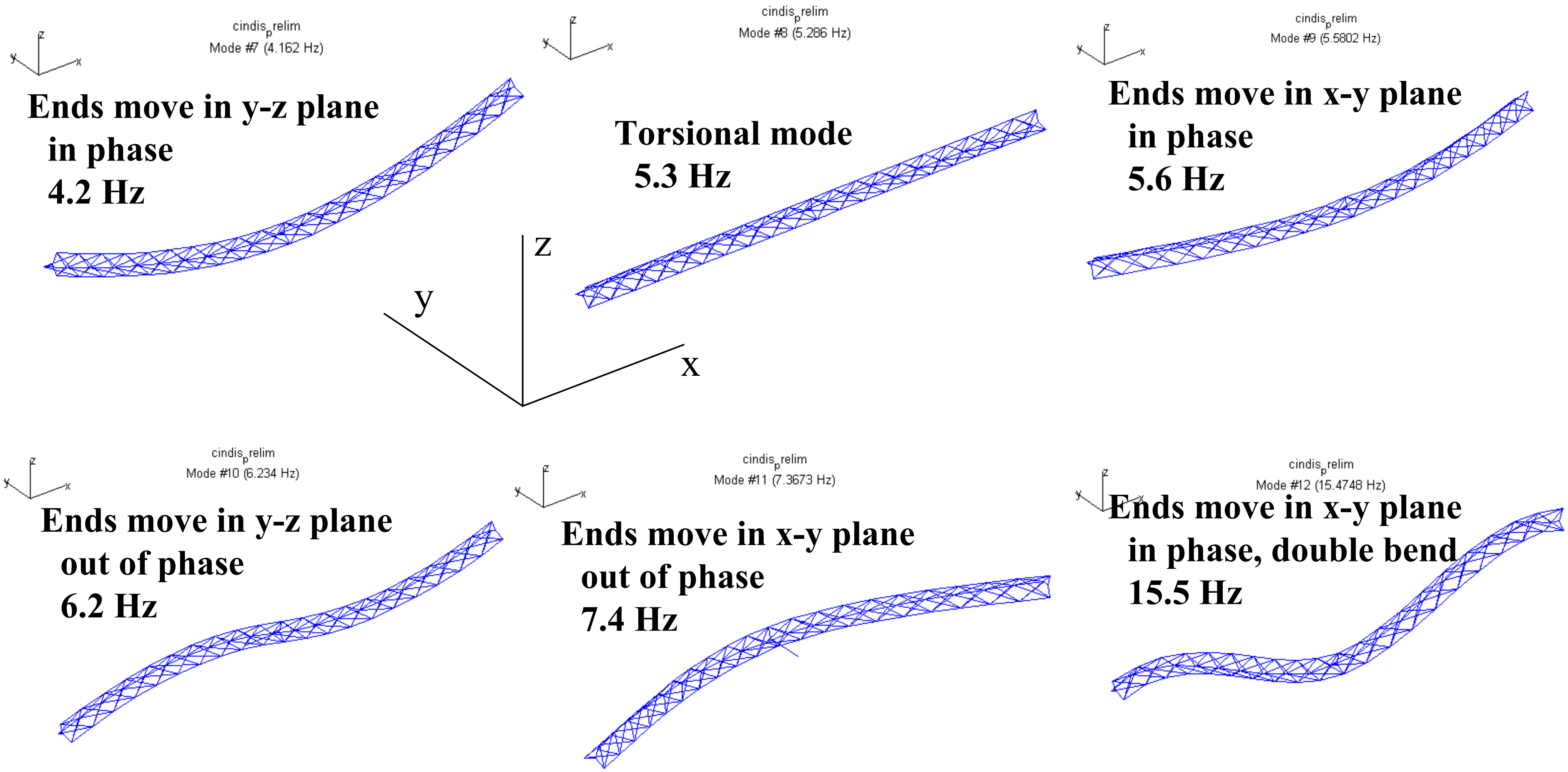






For 30× *smaller* despacing (0.3 nm), stellar leak after spatial filter ~2.5×10^{-9}

First 6 structural bending mode shapes of a 40m truss

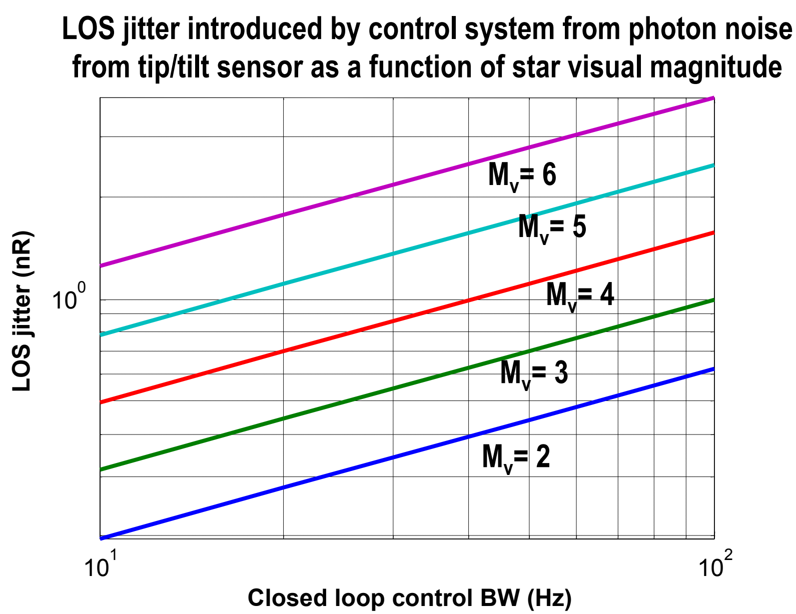


Control System Bandwidth and Sensor Noise

- For rejection at 40 Hz, sample rate must be >1000Hz.
- Assume photon throughput of 10%
  - Photons/update = 1.69×10^4
- Control system rejection greater than 10x for modes with a frequency out to 18 Hz.
- If these limits leave inadequate performance, the base motion must be reduced another way
  - Laser metrology?

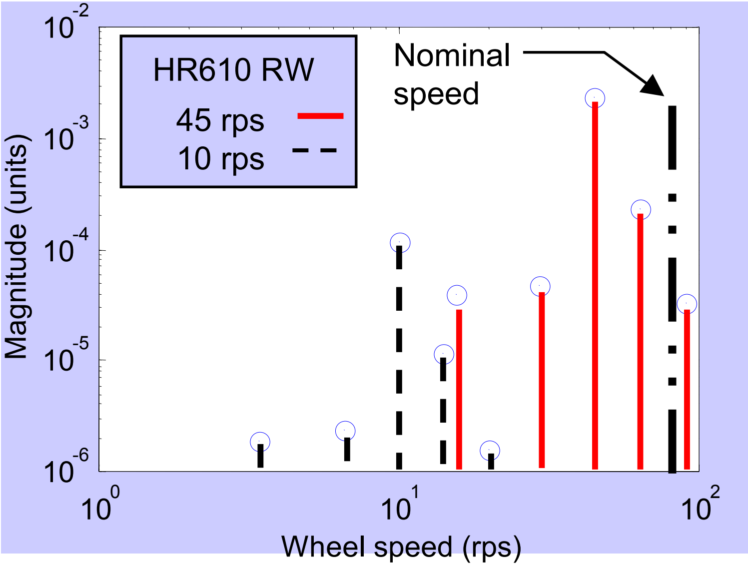
Control system performance for first 6 bending modes

Mode no.	Rejection factor
7	560
8	281
9	222
10	199
11	126
12	14



RW Model - Disturbance Source

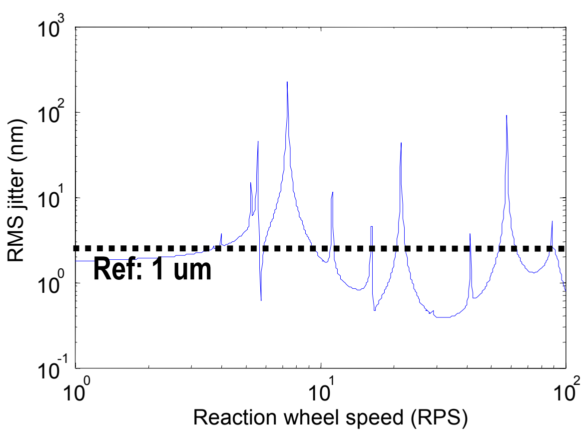
- Cluster of 5 RW on single pallet
- Forcing components increase by (wheel speed)^2. RW internal resonance at 90 Hz included
- Radial forcing harmonics shown in figures for small fast RW (HR0610) Fundamental wheel harmonic (3rd& 4th) provides dominant disturbance.
- Wheels are balanced to HST levels to minimize out-of-balance induced forces and torques.
- Disturbance is applied to the RW node of the coupled structural/optical model



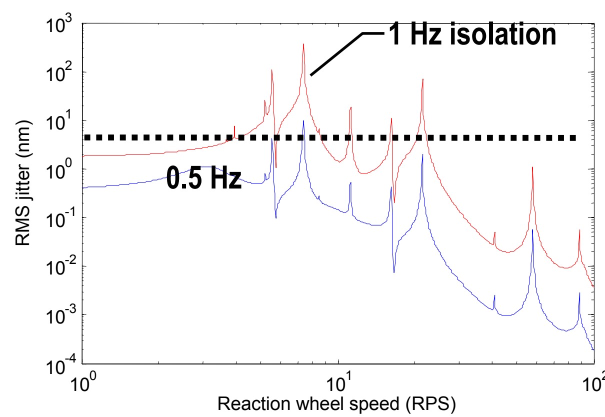
Residual Vibration from Reaction Wheels - Isolation and translation mirror rejection

- Motion of telescopes from RW input, residual jitter is RMS of total displacement vector.
- Isolator natural frequency at 0.5 and 1 Hz
- Control BW's of 10, 20 50, 100 Hz for isolator set at 1 Hz resonance

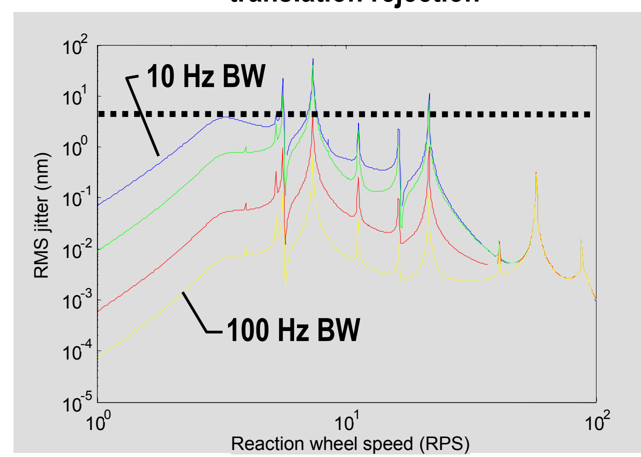
Translation at telescope node (no isolation)



Residual translation after mechanical isolation (0.5 and 1.0 Hz)



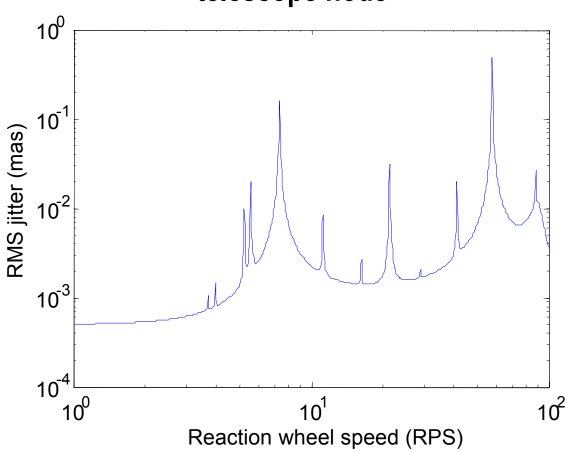
Residual translation after mechanical isolation (1 Hz) and translation rejection



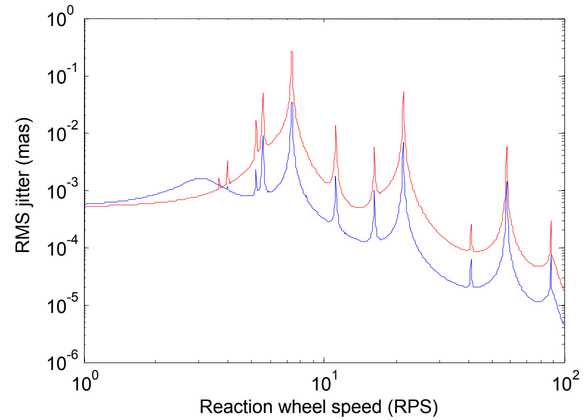
Residual Vibration from Reaction Wheels - Isolation and Fast Steering Mirror rejection

- Motion of telescopes from RW input, residual jitter is RMS of total rotational motion
- Isolator natural frequency at 0.5 and 1 Hz
- Control BW's of 10, 20 50, 100 Hz for isolator set at 1 Hz resonance

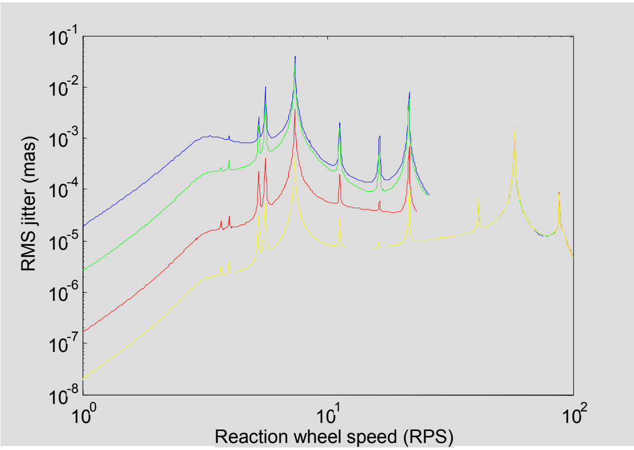
Rotation at telescope node



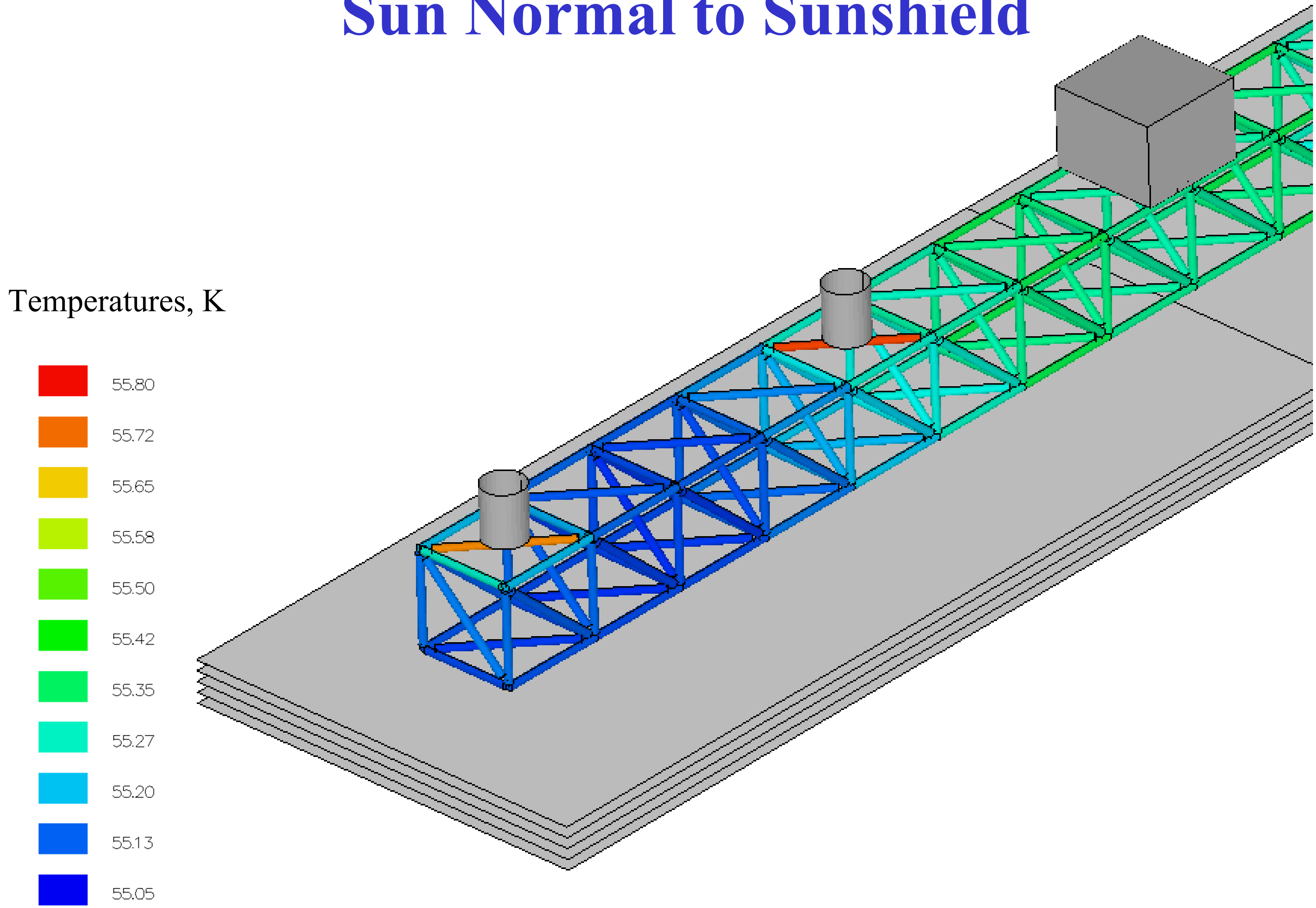
Residual rotation after mechanical isolation



Residual rotation after mechanical isolation and FSM rejection



Temperatures with Beryllium Truss, Sun Normal to Sunshield



Conclusions

- CINDIS Phase 1 was a carefully targeted, conservative, low risk, $300M technology demonstration for TPF
  - Forego scientific objectives to keep cost and cost risk low
  - Tailor instrument to prove instrument technologies to fullest extent
- CINDIS Phase 2 adds compelling science
  - Studies of known extra-solar giant planets, search for others
  - TPF science and technology precursor – advances all key technologies to TRL 8 or 9 except for formation flying interferometry
- Nulling interferometry is hard
  - Chopping architectures (4 apertures or more) are needed for TPF
    - Systematic errors are greatly mitigated, but <u>significant vulnerabilities remain</u>
    - Sensors & controls may tame these new problems, but concepts are complex
  - Stability requirements for chopping architectures are difficult to understand and challenging to achieve
  - Chopping nulling interferometer tech demo needed for TPF